

Biochar: An Overview

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An Introduction to Pyrolysis, Biochar, and Biochar Production

Every year, approximately 1.3 billion tons of biomass is available in the United States for bioenergy production (Perlack *et al.*, 2005; Laird *et al.*, 2009). Biomass is organic material derived from living, or once living organisms, including wood, crops, and plant waste, and animal/human feces. One of the ways to harness the energy available in biomass is through pyrolysis, which is the thermal decomposition of biomass in an environment with a negligible or limited supply of oxygen (Novak *et al.*, 2009a).

Pyrolysis is widely known as the manufacturing process by which charcoal is produced from wood. However, this is a narrow application and pyrolysis sees the transformation of any low-energy-dense biomass into bio-oils (a high-energy-dense liquid), syngas (a low-energy-dense gas), and biochar (a carbon-rich high-energy-dense solid; Laird *et al.*, 2009). Pyrolysis conditions can be optimized to favor the production of a specific product, with slow pyrolysis at lower temperature favoring higher biochar yields and fast pyrolysis at higher temperatures favoring syngas production (Qambrani *et al.*, 2017). Charcoal and Biochar are differentiated through intended use rather than composition or production method; charcoal is solely intended for use as a fuel source while biochar is produced primarily for non-fuel source applications (Lehmann & Joseph, 2009; Qambrani *et al.*, 2017).

Bio-oil may be used directly in home heating devices, or as transportation fuel after further processing, however current production costs exceed bio-oil's value (Braumakis *et al.*, 2014). Syngas can be used for heating, but due to its low heating value, it is often burned to offset the energy cost of pyrolysis and is used to produce electricity or thermal energy (Laird *et al.*, 2009). Biochar has a variety of uses and has been used as a low-yield activated carbon, for filtration of pollutants from wastewater, filtration of pollutants from landfill leachate, carbon sequestration, directly as a fuel source, as a soil application for nutrient retention, to improve crop productivity, soil application for improved water holding capacity, reduce soil emissions, and improve the cation exchange capacity of soil (Lehmann & Joseph, 2009; Qambrani *et al.*, 2017).

Properties of biochar produced from biomass via pyrolysis are highly dependent on many factors, including pyrolysis temperature, heating rate, type and composition of feedstock, particle size, and reactor conditions (Qambrani *et al.*, 2017).

The History of Biochar

The term 'biochar' is a relatively new term within scientific literature and the English vocabulary, having only entered usage in the 20th Century. However, it has previously been studied and referenced under the terms "black lands", "black earth", "dark earth", "terra preta," "terra preta du indio" (Indian black earth in Portuguese), or "Amazonian black earth" (Kawa 2008; Hartt 1874a; Hartt 1874b; Smith 1879; Brown and Lidstone 1878).

Biochar was first referenced in the literature under the term *terra preta* in 1867 when Reverend Ballard S. Dunn wrote *Brazil: the Home for Southerners*. In his book Dunn encouraged other Confederates to migrate to Brazil rather than stay in the defeated South, and referenced the fertile dark land (*terra preta*) found in Brazil...

The dark land, (Terra Preta) is found in some places apparently without admixture with vegetable elements, and in such situations has its color from some sulphureous or carbonaceous ingredient of the soil... the greatest part however of the dark land that is valuable for agricultural purposes... (Dunn 1866: 182-183).

In an attempt to determine the soils fertility and origin, geologists began to travel to Brazil to study *terra preta*. As one geologist, Herber Smith documented...

The cane-field itself is a splendid sight; the stalks ten feet high in many places, and as big as one's wrist. This is the rich terra preta, 'black land,' the best on the Amazons. It is a fine, dark loam, a foot, and often two feet, thick. (Smith 1879: 144)

While the fertility of *terra preta* was widely accepted, up until the 1900s the formation and composition of *terra preta* remained relatively unknown, and was often attributed to the activity of indigenous individuals (Kawa 2008; Niumendajú 2004). Studies conducted from the 1940's till today, however, have further confirmed this theory, with today's experts attributing *terra preta* formation to the actions of indigenous individuals who enriched their farmland with charred ash (Marris 2006).

This research gave evidence for the positive impact that charred organic matter could have on soil, and so the biochar initiative began.

Biochar Properties

PYROLYSIS CONDITIONS

Biochar is the pyrolysis product which contains all non-combustible constituents of the feedstock (ash), and therefore is always present as a product of pyrolysis and gasification, regardless of process temperature and feedstock. Biochar yield is maximized when a slow pyrolysis technique is employed, and conversely biochar yield is minimized under high-temperature fast pyrolysis conditions. Slow pyrolysis employs temperatures ranging from 300-700°C, heating rates from 1-100°C/s, with pyrolysis durations ranging from minutes to days (Qambrani *et al.*, 2017, Cantrell *et al.*, 2012; Spokas *et al.*, 2011).

As biochar can be produced using a variety of methods and feedstocks, its chemical composition and physical properties can vary widely, as can be seen in Table 1 (Smith *et al.*, 2010; Amonette *et al.*, 2008). Analyzing biochar from a single type of feedstock, the pyrolysis temperature, duration, and oxygen exposure all impact the quantity and quality of the biochar formed. However, despite this, there are trends in biochar production.

YIELD AND FIXED CARBON CONTENT

Typically, as the peak pyrolysis temperature increases, the yield of biochar (by weight) decreases, and the carbon content of the biochar (by weight) increases as the hydrogen, nitrogen, and oxygen present in the feedstock are released via the gaseous phase (Mašek *et al.*, 2013). A typical slow pyrolysis process achieves a 35% biochar yield (the fraction of the dry feedstock converted to biochar, by mass), while a typical fast pyrolysis process achieves a 12% biochar yield (Qambrani *et al.*, 2017).

Despite this trend, recent studies have found that low and high temperature pyrolysis produce near identical levels of stable recalcitrant carbon, as a higher stable carbon content product (of lower mass)

is obtained during high temperature pyrolysis, while a lower carbon content product (of higher mass) is obtained during low temperature pyrolysis (Mašek *et al.*, 2013). These results suggest that from a carbon sequestration standpoint, low and high temperature pyrolysis biochars have negligible differences (Mašek *et al.*, 2013). As can be seen in Table 1, however, it is important to note that the carbon content of the biochar can vary widely based on the feedstock selected.

NUTRIENT CONCENTRATION

Potassium (K) and Chlorine (Cl) are vaporized at relatively low-pyrolysis temperatures, while Calcium (Ca), Silicon (Si), and Magnesium (Mg) are vaporized at higher temperatures (Qambrani *et al.*, 2017). The majority of feedstock Phosphorous (P), Sulfur (S), Iron (Fe) and Manganese (Mn) are found in the biochar product, regardless of pyrolysis temperature, while the majority of inorganics are retained as a part of the biochar structure too (Qambrani *et al.*, 2017).

Biochar nutrient concentrations are noted to be significantly higher when feedstocks undergo pyrolysis at higher temperatures (Gaskin *et al.*, 2008), although this is likely due to lower biochar yields associated with higher temperatures. Conversely, Nitrogen (N) concentrations often decrease as pyrolysis temperature increases as it is released into the gaseous phase (Gaskin *et al.*, 2008). Depending on the desired nutrient makeup (N vs. P, K, Ca, and Mg), pyrolysis temperature can be adjusted to optimize the nutrient concentration in the biochar.

Plant derived feedstocks often produce biochars of lower nutrient value due to the loss of nitrogen during the pyrolysis process, and the low nutrient values present in the initial feedstock (Cantrell *et al.*, 2012). Higher nutrient contents in animal and human derived feedstocks may lead to higher nutrient concentrations in biochar produced from these feedstocks. (Cantrell *et al.*, 2012). It is

important to remember, however, that previous research has found that there are no statistically significant correlations between the nutrient quantity in the initial feedstock and the produced biochar. Therefore, initial concentrations should not be used to predict biochar's nutrient quality (Cantrell *et al.*, 2012).

pH

Biochar pH ranges considerably depending on the feedstock from which the biochar was produced. A literature survey by Qambrani *et al.* (2017) found biochar pH may be as low as 5.6, obtained with hardwood feedstock pyrolyzed at 700°C, and as high 12.3, obtained with orange peel feedstock pyrolyzed also at 700°C, although the vast majority of biochar samples were alkaline (pH>7.0).

The pyrolysis temperature – biochar pH relationship has been established with higher pyrolysis temperatures resulting in increased biochar alkalinity (Hossain *et al.*, 2011; Yuan *et al.*, 2011; Cantrell *et al.*, 2012).

SURFACE AREA AND ADSORPTION CAPACITY

Increasing the pyrolysis temperature or exposure time increases the surface area and adsorption capacity of biochar (Kearns *et al.*, 2014; Cantrell *et al.*, 2012). The removal of alkyl-CH₂, ester C=O, aromatic -CO, and phenolic -OH groups from aromatic carbons, in addition to the loss of volatile organic matter that occurs at higher temperatures, is responsible for the subsequent increase in the micropore volume, and therefore an increase in surface area of biochar, as can be seen in Table 1 in the annex (Chen *et al.*, 2008; Lee *et al.* 2010; Ahmad *et al.*, 2012). This increased porous structure enhances biochar properties of water-retention capacity, nutrient retention of soil, and microbial accumulation (Qambrani *et al.*, 2017).

Although pore structure is more organized in biochar produced from plant feedstocks, biochar produced from manure feedstocks possesses excellent fertilizer qualities and heavy metal absorbability (Qambrani *et al.*, 2017).

Uses of Biochar

Uses and applications of biochar is currently a highly active area of research, with research outputs emerging constantly. Below are the contemporary uses of biochar as supported by current literature.

ACTIVATED CARBON SUBSTITUTION

The high carbon content of biochar (65-90%), and high surface areas due to micropores are the two primary properties which provide activated carbon with its notable applications in chemical reactions, filtration/purification, and adsorption applications (Azargohar & Dalai, 2006). Thus, the similarities between biochar and activated carbon have resulted in numerous studies into the applications of biochar as an activated carbon substitute.

Activated carbon has a surface area that typically ranges from 500-1600 m²/g, enabling the aforementioned applications. Biochar produced by low temperature pyrolysis may possess surface area properties as low as 0.7-13.6 m²/g, while biochar produced by high temperature pyrolysis possesses higher surface area properties, as high as 460 m²/g (Qambrani *et al.*, 2017).

Precursor to Activated Carbon

Biochar with high surface area properties may be used directly as a low-yield activated carbon, but biochar with low surface areas are often used as a precursor for activated carbon. When used as a precursor, biochar is first treated with a strong acid or base and then heated to 500-1200 °C (Azargohar & Dalai, 2006). Temperature, chemical reagent choice, chemical reagent to biochar ratio, and nitrogen flow rate all impact the porosity development (Azargohar & Dalai, 2006; Tay *et al.*, 2009). Previous researchers producing activated carbon through this method have created products that had up to 50 times the surface area of the starting material with surface areas as high as 1500 m²/g (Azargohar & Dalai, 2006).

Wastewater Purification

Able to achieve the surface area of activated carbon, biochar has been shown to be a cost-effective alternative to activated carbon, and in some cases biochar has been found to be comparable, or even outperform, activated carbon in water/waste filtration (Kearns *et al.*, 2014; Cao *et al.*, 2009; Hale *et al.*, 2011). With no base/acid treatment and pre/post activation process, biochar is substantially cheaper to produce, with the break-even price of biochar estimated at US \$246 per ton, compared to activated carbon at US \$1500 per ton (Ahmad *et al.*, 2012; Klasson *et al.*, 2009; McCarl *et al.*, 2009).

In water/waste filtration applications biochars function well as sorbents for the removal of both organic and inorganic contaminants, however not all biochars are equivalent in performance. Furthermore, the feedstock used to generate the biochar, in addition to the type of pyrolysis conducted, play key roles in determining the efficacy and type of organic and inorganic contaminants biochar can extract from water, wastewater, and soil. For a full review of biochars and their ability to remove organic (color/dyes, phenols, pesticides, polynuclear aromatics, and solvents) and inorganic (metal ions, anions) contaminants, please see the review conducted by Mohan *et al.*, 2014.

Although biochars vary widely in their filtration abilities, some trends do emerge. In general, as pyrolysis temperatures increase, so does the biochar's ability to uptake/filter out contaminants (most likely from the subsequent increase in surface area; Kearns *et al.*, 2014). Biochars produced at lower temperatures are better at removing inorganic compounds as they contain a larger proportion of their original organic matter in the biochar (Kearns *et al.*, 2014). Due to the retention of their original organic matter, however, low temperature biochars are often ineffective at removing pesticides and other compounds. While these biochars can initially

adsorb these compounds, these biochars often desorb the pesticides and other organic compounds as time progresses. This subsequent desorption has caused some researchers to propose that these biochars could be used in pest and herbicide application, as it would avoid mass spraying and the aerosolization of toxic pesticides (herbicide applied to biochar, and then to field; Kearns *et al.*, 2014; Li *et al.*, 2013).

Additionally, biochars produced from crop residues, peat, and wood are generally only effective at adsorbing organic contaminants, while biochars produced from some manures are often very effective at adsorbing organic, and inorganic contaminants due to their high phosphorous content (Cao *et al.*, 2009). Two studies reported in 2009 that biochar performed better than commercially available activated carbon for the adsorption of lead (Cao *et al.*, 2009; Lu *et al.*, 2009).

Additional studies have established a trend where biochars with differing active compounds, resulting properties from differing feedstock compositions, gain the ability to adsorb heavy metals, including aluminium (Al) and manganese (Mn) in acid soils, and arsenic (As), cadmium (Cd), copper (Cu), nickel (Ni) and lead (Pb) in soils with heavy metal contamination. Cu(II) compounds were removed by biochar featuring carboxylic active groups, Pb(II) with hydroxyl groups, and Al(III) with active groups containing oxygen (Qambrani *et al.*, 2017). Most of these heavy metals compounds were adsorbed on the biochar surface due inorganic constituent makeup within the biochar, as a result of the manure feedstocks.

Due to biochar's effectiveness in adsorbing organic/inorganic contaminants, biochar is a logical option for applications in which high-cost traditional activated carbon would be unfeasible, such as storm drains, municipal water treatment, agricultural run-off control, or water/wastewater treatment in low-income or rural areas (Kearns *et al.*, 2014).

STORMWATER REMEDIATION

Mohanty *et al.* (2018) investigated the potential applications of biochar for stormwater contaminant removal, and demonstrated that inclusion of biochar media in stormwater remediation experiments resulted in significant performance for metalloid/metal-ion adsorption and removal, organic contaminant removal, nutrient removal, and biological contaminant deactivation and removal. The study concluded that the three primary functions of biochar for stormwater remediation applications are soil amendment for plant growth that may increase the removal of nutrients, filter media for contaminant removal, and hydraulic and redox manipulation of the geomedia layers to further enhance contaminant removal.

Mohanty *et al.* (2018) also highlighted potential benefits of biochar inclusion in low impact development systems to increase removal of stormwater contaminants, including downspout filter boxes, tree boxes, green roofs, bioinfiltration and bioretention systems, natural and constructed wetlands, sand filters, swales, infiltration trenches, and wet retention ponds.

Miles *et al.* (2016) motivated that, based on feasibility, economical viability and performance improvements, biochar should be integrated into filtration media used in stormwater best management practices for both new constructions and retrofit applications. This study similarly specifically considered current systems, such as planted filter boxes, media filters, bioretention systems, green roofs, denitrification bioreactors, and sand filters (Miles *et al.* 2016).

ODOR CONTROL

Like activated carbon, biochar sees frequent use for its odor control abilities. Studies on the adsorption of airborne molecules responsible for fecal malodor showed that biochars derived from bamboo wood, pine wood, and human feces, performed equal to each other and with an activated carbon control for odor adsorption performance (Stetina, 2017). Whilst 100% faecal malodor was not achieved.

SOIL AMENDMENT

While there are many studies that analyzed the effect of biochar addition on soil and crop productivity, the results vary widely. In terms of crop productivity, a meta-analysis conducted by Jeffery *et al.* found that across the fourteen studies analyzed there was a slight, statistically significant, positive impact on crop productivity across the studies, improving crop productivity/yield by 10%. Although the change in crop yield varied widely (-28 to +39%) the greatest improvements were often seen when biochar was added to acidic or pH-neutral soils, and to those with medium/coarse textures (Jeffery *et al.*, 2011). Biochar additions of 100 tons/hectare showed the greatest improvement in crop yield (+39%; Jeffery *et al.*, 2011). It is important to note that other studies have documented increases in crop yields from +64% (Hossain *et al.*, 2010), to +146% (Peng *et al.*, 2011) to +250% (Van Zwieten *et al.*, 2010), with the greatest improvements often seen when biochar was added in addition to fertilizer, with only modest improvements observed when added independently (Hossain *et al.*, 2010; Van Zwieten *et al.*, 2010; Peng *et al.*, 2011).

Although the results vary widely, studies have also shown that biochar addition to soil can improve the soil's water retention ability (Karhu *et al.*, 2011; Peng *et al.*, 2011; Ding *et al.*, 2010; Basso *et al.*, 2013), pH (potential substitute for agricultural lime; Peng *et al.*, 2011, Novak *et al.*, 2009b; Collins, 2008; Galinato *et al.*, 2011), cation exchange capacity (Peng *et al.*, 2011; Van Zwieten *et al.*, 2010), nutrient retention (Ding *et al.*, 2010), and soil biota (Atkinson *et al.*, 2010; Solaiman *et al.*, 2010; Warnock *et al.*, 2010), while reducing soil emissions (Karhu *et al.*, 2011). However, it is known that pyrolysis temperature, pyrolysis duration, the initial feedstock, the amount of biochar added, and the initial chemical composition of the soil all impact the biochar's ability to positively impact the soil and crop yield. In addition, all of the previously cited studies have been conducted over a time period of months to two years, and no long-term studies have been done on the impact of biochar to soil (Jeffery *et al.*, 2011). While biochar can effectively be used to eliminate soil contaminants (as discussed earlier), the widespread adoption of biochar as a soil additive should not be done until more research is done on the pyrolysis conditions, feedstocks, initial soil qualities, and the amount of biochar that should be added to maximize biochar's positive effect. Until these variables are optimized and long-term studies have been conducted, it is difficult to assess biochar's value as a soil additive.

SOLID WASTE MANAGEMENT

Biochar's similarities to activated-carbon has stimulated research of biochar applications to conventional solid waste management practices. In large scale landfill operations, biochar has been noted to contribute to leachate remediation, lessening the environmental impact of the landfill sites, while small scale composting operations for organic solid waste management see increased composting performance when biochar is added to composting feedstocks (Qambrani *et al.*, 2017).

Landfill Leachate Remediation

Open landfills are a conventional solid waste management technique to dispose of waste generated by human activity. Whilst this technique is both effective and cost-effective for centralised containment of solid wastes, large operations often lead to a toxic cocktail of acids, volatile organic compounds, pharmaceuticals, pesticides and heavy metals discharged to the environment, without treatment, as landfill leachate (Jayawardhana *et al.*, 2016).

Shehzad *et al.* (2016) used activated biochar produced from sea mango to demonstrate the potential of biochar for the adsorptive treatment of inorganic and organic compounds in landfill leachates. Under ideal conditions, activated biochar was shown to achieve a leachate remediation performance of 95.1% color reduction, 84.94% COD removal, and 95.77% NH₃-N removal through adsorption (Shehzad *et al.*, 2016). Additionally, Gao *et al.* (2013) demonstrated that while activated carbon performed best of all evaluated mediums, two biochars each derived from low-temperature pyrolysis of swine manure and woody biomass were effective mediums for the sorption of phthalic acid esters from landfill leachate.

Organic Solid Waste Composting Additives

The influence of biochar additives to organic solid waste composting feeds has been shown through many studies to improve the performance of the composting process and quality of compost products. In a meta-analysis of the influence of different biochar additives on composting performance by Xiao *et al.* (2017), the following composting performance improvements have been measured across various studies:

- Increased pH with increasing biochar addition rates
- Increased peak pile temperature with increasing biochar addition rates
- Increased Cu²⁺ and Zn²⁺ stability (decreased mobility)
- Enhanced organic matter degradation/reduction and compost maturity
- Accelerated decomposition and humification
- Increased germination index values
- Enhanced aeration
- Reduced total N₂O emissions
- Reduced total NH₃ emissions
- Increased CO₂ emissions
- Overall reduction of GHG emissions
- Higher microbial activity (higher respiration rates)
- Improved compost medium porosity

Overall, the meta-analysis indicates that biochar additives benefits for composting in solid waste management practices. However, the meta-analysis also identified that all mechanisms by which composting performance gains are achieved and the relationship between biochar and microbial communities are not fully understood and require further research.

GREENHOUSE GAS EMISSION REDUCTION

Carbon Stability

Biochar's carbon sequestration potential is rooted in its carbon stability, which prevents the carbon present in biochar from near-term decomposition into lighter hydrocarbons, including the release of greenhouse gases, like CO₂ or CH₄ to the atmosphere. The longer biochar can maintain its structure (higher carbon stability) and prevent its carbon from re-entering the atmosphere, the greater role biochar can have in carbon sequestration plans. Often biochar's carbon stability is measured by determining the half-life, or mean residence time of the carbon in the biochar. The half-life refers to the amount of time it takes for half of the carbon present in the initial biochar to degrade (similar to a median), while the mean residence time refers to the average time that the carbon spends in the soil before it returns to the atmosphere (similar to the mean).

The feedstock type, pyrolysis conditions, and the soil to which the biochar is added are all known to affect biochar half-life/mean residence time (Fang et al., 2014; Singh et al., 2012), and current studies have shown that biochar's mean residence time can vary from 44-10,000 years depending on these conditions (Fang et al., 2014 [mean residence time: 44-610]; Kuzyakov et al., 2009 [mean residence

time: 2,000, half-life 1,400]; Singh et al., 2012 [mean residence time: 90-1,616]; Peng et al., 2011 [mean residence time: 244-1,700]; Qambrani et al., 2017 [mean residence time: 1,000-10,000]). However, it should also be noted that precise long-term stability of biochar is a difficult property to measure accurately, due to the nature of recalcitrant carbons (Lehmann, 2007).

Singh et al. conducted a 5-year laboratory study that exemplifies how biochar's carbon stability can vary based on feedstock (Eucalyptus saligna wood and leaves, paper mill sludge, poultry litter, cow manure) and pyrolysis conditions. Using carbon-13 testing to determine the stability of the biochar, researchers found that 0.5-8.9% of the biochar was mineralized over the 5 year study period (Singh et al., 2012). Singh et al. found a wide range in the mean residence time of the biochar, ranging from 90-1600 years depending on the feedstock and pyrolysis conditions, as can be seen in Table 2 below. Biochars made from manure feedstocks, and biochars produced at lower pyrolysis temperatures had lower carbon stabilities (Singh et al., 2012).

Ladygina & Rineau describe similar variations in biochar's half-life/mean residence time due to feedstock selection and pyrolysis conditions, reporting mean residence times that vary from 3-658 years based on the conditions. As biochar's carbon stability determines its carbon sequestration

Table 2: Carbon Stability of Biochar

FEEDSTOCK	TEMPERATURE	STEAM ACTIVATION	CARBON MEAN RESIDENCE TIME (YEARS)
Eucalyptus saligna wood	400°C	Yes	326
Eucalyptus saligna wood	400°C	No	294
Eucalyptus saligna wood	550°C	Yes	1271
Eucalyptus saligna wood	550°C	No	1616
Eucalyptus saligna leaves	400°C	Yes	270
Eucalyptus saligna leaves	550°C	Yes	572
Paper mill sludge	550°C	Yes	102
Poultry litter	400°C	No	129
Poultry litter	550°C	Yes	396
Cow manure	400°C	No	90
Cow manure	550°C	Yes	313

Note: Results adapted from Singh et al., 2012.

potential, the soil conditions, feedstock, and pyrolysis conditions must first be optimized before one can assess its carbon sequestration potential (Woolf et al., 2010).

Carbon Sequestration

One of the proposed solutions to address the increase in atmospheric concentrations of CO₂ and the continually rising levels of anthropogenic CO₂ emissions has been carbon sequestration through biochar production. Various researchers and biochar advocates have proposed that biochar production could offset national US greenhouse emissions by up to 12% annually (or about 1.8 PgCO₂-C; Woolf et al., 2010) when the process is optimized for biochar production, and up to 10% annually when the process is optimized for bioenergy production, which is by far superior to other currently used carbon sequestration techniques.

Forestation, no tillage areas, and slash and burn practices have previously been used in an attempt to sequester carbon. However, while new forests can sequester a substantial amount of CO₂ initially, as these forests mature they begin to release as much CO₂ as they sequester (Lehmann 2007). Agricultural lands that are converted to no-tillage areas also sequester carbon initially, but after 10-15 years these areas encounter a similar phenomenon and begin to release as much CO₂ as they offset (Lehmann 2007). Used extensively worldwide, slash and burn land conversion only sequesters 2-3% of the initial carbon present in the biomass (due to the oxygen abundant burn conditions; opposed to roughly 30% with biochar), and only 0.2-0.6% of the carbon has been found to remain in the ground after 5-10 years (Atkinson et al., 2010).

The proposed carbon sequestration techniques through biochar production involve the mass pyrolysis of crop residues, animal manures, and forest residues on a national and/or global basis. As biochar can be produced at any level, from industrial to domestic production, biochar production can become a viable option independent of socioeconomic status (Woolf et al., 2010).

In order to sequester 12% of the global CO₂ emissions, Woolf et al. proposes a plan where 2.27 Pg-C (roughly 5 trillion lbs) of biomass would be converted to biochar annually. Obtaining biochar from waste sources, biochar production would not affect current land use or food production (for more information on the developed plan, please see Woolf et al., 2010).

Other variations of carbon sequestration techniques through biochar production emphasize fuel displacement. By optimizing bioenergy production in the biochar production process, researchers estimated that by harvesting 1.1 billion tons of biomass from US croplands, one could offset 25% of the US's fossil fuel consumption. Through fossil fuel displacement, biochar production, and carbon sequestration, it was estimated that this technique could offset about 10% of the annual US CO₂ emissions (Galinato et al., 2011; Laird 2008).

In order for biochar sequestration techniques to be successful, the biomass cannot be obtained from land clearance, food sources, or created in in-efficient burners. Land clearance cannot be a part of generating feedstocks for biochar production as this destroys valuable ecosystems and releases carbon stored in biomass and soil, "...leading to carbon payback times in excess of 50 years" (Woolf et al. 2010:3). Agricultural lands used for food production cannot be transferred to biomass crops for biochar production, as this would negatively impact food security and stimulate land clearing in other locations (Woolf et al., 2010). Finally, modern pyrolysis technology (low emissions, high biochar yield) would have to be used in the biochar production process, as the emissions from inefficient biochar units can quickly negate any benefits.

Before any of these plans could be implemented however, more research will need to be conducted on the carbon stability of biochar, and the ways in which the pyrolysis conditions and feedstock can be used to optimize biochar's carbon stability. As biochar's carbon sequestration is based upon biochar's ability to slow carbon's release into the atmosphere, biochar's carbon stability must first

be optimized before one can assess its carbon sequestration potential (Woolf *et al.*, 2010).

In-order to allow biochar to be an economically feasible option for carbon sequestration, biochar production must first be recognized by a carbon market as an accepted carbon sequestration technique. Currently, under the Kyoto Protocol developed by the United Nations Framework on Climate Change (UNFCCC), biochar does not qualify as an accepted carbon sequestration method (Galinato *et al.*, 2011). Until national or global carbon markets recognize biochar, it is unlikely that biochar will be an economically feasible option for agricultural soil amendment or climate change mitigation (Galinato *et al.*, 2011).

BIOCHAR USES IN FOOD AND MEDICINE

As of 2014, there have been no studies conducted to evaluate biochar's role in food and medicine. While biochar remains a key ingredient in many herbal treatments and supplements, biochar's effectiveness has yet to be proven scientifically in these applications. Used as a low-grade activated carbon, however, biochar could have future uses in medicine, particularly in rural and low-income areas where activated carbon is not readily available, although further research would need to be conducted to support this use.

Due to activated carbon's high adsorption properties, it is regularly used in medicine to remove various drugs or toxins from the gastrointestinal system, and has been shown to be more effective at drug/toxin elimination than stomach pumping (Neuvonen & Olkkola, 1988). Activated carbon can help eliminate toxins even after systematic adsorption, although it is most effective at adsorbing toxins and drugs present in the stomach at the time of consumption, and to maximize effectiveness, activated carbon must be taken as soon as possible after intoxication. Activated carbon cannot adsorb alcohol, cyanide, and specific heavy metals, such as lithium and iron (Neuvonen & Olkkola, 1988).

INFRASTRUCTURE APPLICATIONS

A study on the potential of biochar as a bio-modifier for asphalts (Zhao *et al.*, 2014) concluded that biochar is an effective additive to bitumen binder to increase resistance to the pavement engineering challenges of ageing, rutting, moisture ingress and fatigue cracking.

Several asphalt binder compositions were created, including a virgin asphalt binder, commercially activated carbon, biochar from slow pyrolysis and biochar from fast pyrolysis, and were tested for rheological properties, such as binder performance and ductility. Results showed that the rheological properties of the virgin binder were improved by all carbon-rich additives at high temperatures, indicating that ageing of the binder can be delayed significantly when modified. Barely any effect was observed at low temperatures, when compared to the virgin binder, showing that the treatment does not have adverse effects during colder seasons. However, biochar-enhanced asphalts seemed to be more effective at providing rutting resistance than activated carbon (Zhao *et al.*, 2014).

Overall, carbon-rich enhancement of asphalt binders were shown to be effective in improving binder performance and slowing binder degeneration during service, especially for high temperature performance, ageing and rutting (Zhao *et al.*, 2014).

Biochar and Human Waste

The conversion of human waste to biochar has applications in both developing and developed countries. In developing countries biochar production technology is driven primarily by the need for sanitation and energy production rather than the associated benefits of biochar.

Currently, 2.5 billion individuals do not have access to proper sanitation services, and of those approximately 1 billion practice open defecation. This represents a major public health concern as improper sanitation services and open defecation allow bacteria, parasites, and viruses present in human waste to contaminate water, food, and soil (WHO 2008). This can lead to cholera, hepatitis, polio, worm infestation, and diarrhea. In fact, water contamination from human waste is one of the leading causes of diarrhea worldwide, and the second leading cause of death for children in developing countries (WHO 2008). One of the proposed solutions to alleviate this problem has been to convert raw human waste into biochar. This has been proposed for a variety of reasons, including:

- 1) due to the high temperatures achieved in pyrolysis process, all pathogens and organic toxins present in the human waste would be destroyed (Laird *et al.*, 2009);
- 2) pyrolysis provides a method for significantly reducing waste stream volume (Cantrell *et al.*, 2012; see Table 1);
- 3) pyrolysis of human waste provides a net energy output, which could be used to generate heat or electricity in rural or low-income applications (Liu *et al.*, 2014); and,

- 4) pyrolysis creates an end value-added usable product, biochar, which could be used in any of the applications previously mentioned in this paper, including fuel (Cantrell *et al.*, 2012).

From an energy standpoint, human waste can vary widely in energy content from 12.4 to 18.12 MJ/kg, presumably due to variation in diet and moisture content (Zanoni & Mueller, 1982; Liu *et al.*, 2014). Despite this variation, when human waste (at 18.12 MJ/kg) undergoes pyrolysis at moisture levels below 57%, a biochar pyrolysis unit can harvest the produced biochar and still have a net energy output in the form of heat or electricity (Liu *et al.*, 2014). This energy output can be increased by employing a solar (or other method) pre-dryer to obtain feedstock with moisture levels below 57%, or by using the biochar for fuel (Liu *et al.*, 2014). Working in developing countries Ward *et al.* (2014), developed a method of creating briquettes made with 10% starch and 90% biochar from human waste that an energy content of 25 MJ/kg, comparable to that of charcoal. These briquettes could then be used for home heating or cooking applications in rural and/or low-income communities.

In contrast to the needs in developing countries, biochar technology in developed countries is primarily focused around waste reduction, and the generation and use of the final biochar product. Due to the availability of other feedstocks for these purposes, however, few units have been designed in developed countries for the pyrolysis of human waste.

The Safety of Biochar Production and Use

There are four safety concerns that ought to be addressed when producing and using biochar.

Firstly, as biochar is produced under a negligible or limited supply of oxygen, pyrolysis units by definition are undergoing incomplete combustion and there is a potential that these units could emit high levels of particulate matter and other pollutants. Technology currently developed for biomass combustion products could be applied to this technology, however, and further reduce/eliminate this problem (Hallowell, 2014). Currently unregulated at the national level, in November of 2014 the EPA defined biochar for the first time in the “*Framework for Assessing Biogenic CO₂ Emissions from Stationary Sources*” where they recognized biochar production as a potential source for significant air pollution. While there are currently no emissions regulations in place at the federal level for biochar production units, as the use and production of biochar continues to expand, they will likely be developed/enforced.

Second, biochars produced by some pyrolyzers (specifically fast pyrolyzers) are produced as fine powder, and if stored or produced in an area with exposure to oxygen and moisture, pose a significant explosive hazard (Laird et al., 2009). Ideally, biochar will be required to be output as a granulated carbon with an effective diameter particle size larger than 1 mm, to negate any chance of dust explosion.

Third, the application of biochar to soil for agricultural purposes will cause significant particulate matter production, which could harm those working and living near the agricultural site (Laird et al., 2009). Researchers have posed that by producing biochar in slurry, or by mixing it with water or manure, the explosive and particulate matter safety concerns (that occurred when spreading it) could be eliminated (Laird et al., 2009).

Fourth, studies have found that biochar can be a significant source and retainer of polycyclic aromatic hydrocarbons (PAHs) and more research

needs to be conducted to determine the feedstocks and pyrolysis conditions that minimize PAH concentrations before biochar’s widespread acceptance/addition to soil (Keiluweit et al., 2012; Quilliam et al., 2013).

Polycyclic aromatic hydrocarbons (PAHs) are produced when there is incomplete combustion of biomass. Once formed, PAHs can be released into the air via combustion emissions, or they can build up in biochar and ash. Besides causing environmental damage, PAHs are carcinogenic, can increase the risk of cardiovascular disease, and can cause birth defects. While combustion emissions can be limited using pollution control technology, the levels of PAHs present in some biochars can negatively impact the environment, depending on the application rate, soil use, and the original concentration of PAHs in the soil (Fabbri et al., 2013). Soil contamination is an issue as plants grown in PAH contaminated soil or water can accumulate PAHs, which are then ingested by humans or other organisms (Rogovska et al., 2012). In general, leafy vegetables (as opposed to fruit or root crops) accumulate higher levels of PAHs when grown in contaminated soils (Fabbri et al., 2013).

Fortunately, pyrolysis conditions and feedstock type can be modified to minimize the production of PAHs (Keiluweit et al., 2012; Rogovska et al., 2012; Fabbri et al., 2013). Studying the production of PAHs at various pyrolysis temperatures, researchers have found biochar pyrolyzed at 400-600°C produces significantly more PAHs than those produced at higher or lower temperatures (Keiluweit et al., 2012; Hale et al., 2012b). As pyrolysis time increased PAH concentrations also decreased (Hale et al., 2012b). Grass based biomass produce more PAHs during pyrolysis than wood biomass (Keiluweit et al., 2012).

In the United States, the legal limit of allowable PAH concentrations for biosolids considered for the application to agricultural land is 6 mg/kg,

with legal limits in Europe ranging from 3-6 mg/kg (Keiluweit *et al.*, 2012). With respect to biochar, however, it is important to distinguish between PAH concentrations, and PAH concentrations that are bioavailable.

In the production of biochar, high temperature pyrolysis is preferred, as the end product not only has lower levels of PAHs, but a higher surface area (Keiluweit *et al.*, 2012). While this biochar may contain measurable PAH concentrations, it is adsorbed to the biochar, and not bioavailable for the contamination of crops and waterways (Rogovska *et al.*, 2012). Due to the high surface area of biochar produced at higher pyrolysis temperatures, it is also effective at extracting PAH contamination from soils.

As an example, Khan *et al.*, produced biochars from peanut shells, sewage sludge, soybean straw, and rice straw (PAH concentrations of 1.5, 1.7, 2.5, and 6.0 $\mu\text{g/kg}$ respectively) and added them (at 2 and 5% by weight) to soil contaminated with PAHs (concentration 10.2 $\mu\text{g/kg}$; Khan *et al.*, 2015). The bioavailability of PAHs was then measured by growing turnips in the amended, and un-amended soils. Khan *et al.* found that biochar additions significantly reduced the accumulation of PAHs in turnips, with additions of 5% significantly more effective than 2% at removing PAHs. Biochar additions also significantly reduced the presence of potential toxic elements, including As, Cd, Cu, Pb, and Zn from accumulating in the turnips (Khan *et al.*, 2015).

To determine if the pyrolysis process significantly altered PAH concentrations, relative to the initial feedstock, Zielińska & Oleszczuk pyrolyzed sewage sludge at various temperatures. They found that the pyrolysis process significantly reduced PAH concentrations when compared to the initial biomass, from 8- to 25-fold, depending on the pyrolysis conditions and sludge type (Zielińska & Oleszczuk, 2015). In addition to significant reductions in overall PAH concentrations, pyrolysis also significantly reduced concentrations of the most hazardous PAHs (Zielińska & Oleszczuk, 2015).

By pyrolyzing biomass at high temperatures, for extended periods of time, and testing PAH concentrations in the produced biochar, manufacturers can assure the quality of biochar being produced and the positive impact it will have on the environment and human health (Rogovska *et al.*, 2012). In addition to these measures, pyrolyzers themselves can also be optimized to reduce biochar's exposure and contamination with PAHs through unique structural design changes in the pyrolyzer itself (Hallowell & Hallowell, 2015).

It is important to note that naturally in soil, PAH concentrations are gradually lowered through evaporation, biodegradation, or abiotic degradation (Fabbri *et al.*, 2013). If trapped in biochar, however, PAHs remain stable, and may build up in the soil, although they will not be bioavailable (Fabbri *et al.*, 2013). At this time, however, no studies have been conducted to determine the stability of the adsorbed PAHs long-term.

Further Research

This paper has identified a number of areas in which further research into biochar and its uses have yet to be done.

Further research is required to fully understand the carbon stability of created biochars, and to determine the feedstocks and pyrolysis conditions that optimize its carbon lifespan in order to accurately predict the carbon sequestration which can be achieved for various feedstocks.

While biochar can effectively be used to eliminate soil contaminants, more research is required to establish the relationships between pyrolysis conditions, feedstock properties, initial soil qualities, the amount of biochar that should be added to maximize biochar's positive effect, and crop yield. Until these variables are optimized and long-term studies have been concluded with scientific consensus, it is difficult to conclusively assess biochar's quantitative value as a soil additive.

Conclusion

The pyrolysis process has been shown to be an effective technique to generate renewable electricity, heat, liquid bio-oil, syngas, and biochar. Biochar has many current, potential, and theoretical future applications, all of which are current areas of intense research. Among the current uses of biochar lies its great untapped potential for use as a fuel source, low-grade activated carbon, mechanism for human waste disposal, and wastewater, stormwater and landfill leachate remediation.

Due to biochar's effectiveness in adsorbing organic/inorganic contaminants, biochar is a logical option for applications in which conventional high-cost activated carbon would be unfeasible, such as stormwater remediation, municipal water treatment, agricultural run-off control, odor control, and water/wastewater treatment in low-income or rural areas. In the disposal of human waste, the biochar production process can effectively: 1) destroy all pathogens and organic toxins present; 2) significantly reduce waste stream volume; 3) provide a net energy output; and 4) create an end usable product, which could be used for any of the applications previously mentioned.

Although biochar is currently marketed as a carbon sequestration technique and soil additive, there is not enough scientifically backed evidence to support the widespread adoption of all biochars from all feedstocks for these uses at this time. Further research needs to be conducted to optimize the pyrolysis conditions and feedstock properties that optimize its carbon stability to accurately quantify the carbon sequestration achieved.

While biochar's addition to soil generally improves crop yield, water retention, cation exchange capacity, and healthy soil biota, not all additions of biochar to soil produce positive effects, with some biochar additions negatively impacting the soil in all of these areas. No studies have currently evaluated biochar's long-term impact to soil to determine long-term returns on agricultural biochar applications. Future research needs to be done to determine the feedstocks, pyrolysis conditions, initial soil compositions, and the amount of biochar that needs to be added to maximize the longevity and the efficacy of biochars addition to soil.

The addition of biochar to organic feeds for composting as a organic solid waste management technique generally shows that biochar increases composting performance and composting quality.

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Appendix

Table 1: Properties of biochars produced via pyrolysis, and associated feedstocks and pyrolysis conditions

FEEDSTOCK	% MOISTURE	PYROLYSIS TEMP	BIOCHAR YIELD WT%	STABLE CARBON YIELD	SURFACE AREA M2/G	PH	OTHER	CITATION
Corn Cob	11.7%	300°C	77.3%	49.1%	61.8	8.1		Liu et al., 2014
Corn Cob	11.7%	400°C	36.9%	71.7%	180.1	9.1		Liu et al., 2014
Corn Cob	11.7%	500°C	23.3%	81.6%	212.6	9.3		Liu et al., 2014
Corn Cob	11.7%	600°C	21.7%	82.4%	192.9	10.4		Liu et al., 2014
Corn Stalk	8.4%	500°C	30.9%	76.6%	201.3	10.1		Liu et al., 2014
Corn Stover	Dried and ground, <10%	500°C	33.2%	54.7%	20.9		Nitrogen purge 1L/min 50g for 30m	Brewer et al., 2009
Corn Stover	Dried and ground, <10%	500°C	n/a	34.4%	7.0		Performed on a 5kg/h capacity bubbling fluidized bed reactor	Brewer et al., 2009
Corn Stover	Dried and ground, <10%	730 °C	n/a	38.5%	23.9		3 kg/h capacity bubbling fluidized bed reactor using an air/nitrogen fluidizing gas	Brewer et al., 2009
Dairy Manure	Dried 0.31%-6.49%	350 °C	54.9%	23.2%	1.64	9.2	Nitrogen purge 1L/min	Cantrell et al., 2012
Dairy Manure	Dried 0.31%-6.49%	700 °C	35.0%	34.7%	186.5	9.9	Nitrogen purge 1L/min	Cantrell et al., 2012
Feedlot Manure (manure with cornstalk bedding)	Dried 0.31%-6.49%	350 °C	51.1%	23.5%	1.34	9.1	Nitrogen purge 1L/min	Cantrell et al., 2012
Feedlot Manure	Dried 0.31%-6.49%	700 °C	32.2%	36.3%	145.2	10.3	Nitrogen purge 1L/min	Cantrell et al., 2012
Goat Manure	Oven dried, 8.7%	400 °C	44.5%	31% est.	3.27			Touray et al., 2014
Goat Manure	Oven dried, 8.7%	500 °C	40.6%	36% est.	1.68			Touray et al., 2014
Goat Manure	Oven dried, 8.7%	600 °C	37.9%	38% est.	13.92			Touray et al., 2014

Table 1: Properties of biochars produced via pyrolysis, and associated feedstocks and pyrolysis conditions (*continued*)

FEEDSTOCK	% MOISTURE	PYROLYSIS TEMP	BIOCHAR YIELD WT%	STABLE CARBON YIELD	SURFACE AREA M2/G	PH	OTHER	CITATION
Goat Manure	Oven dried, 8.7%	700 °C	35.5%	36% est.	39.08			Touray <i>et al.</i> , 2014
Goat Manure	Oven dried, 8.7%	800 °C	33.8%	35% est.	93.49			Touray <i>et al.</i> , 2014
Mixed larch and spruce wood chips	30%	350 °C	44% est.	72% est.				Masek <i>et al.</i> , 2013
Mixed larch and spruce wood chips	30%	450 °C	36% est.	78% est.				Masek <i>et al.</i> , 2013
Mixed larch and spruce wood chips	30%	550 °C	30% est.	86% est.				Masek <i>et al.</i> , 2013
Paper Mill Waste		550 °C	32%	50%	114.9	9.4	32.6% (by mass) enhanced solids reduction (ESR) sludge, 18.8% clarifier sludge and 48.6% waste wood chips	Van Zwieten <i>et al.</i> , 2010
Paper Mill Waste		550 °C	29%	52%	114.9	8.2	19.5% ESR sludge, 11.2% clarifier sludge and 69.3% waste wood chips	Van Zwieten <i>et al.</i> , 2010
Peanut Shells	Dried, % n/a	300 °C	36.91%	68.27%	3.14	7.76		Ahmad <i>et al.</i> , 2012
Peanut Shells	Dried, % n/a	700 °C	21.89%	83.76	448.2	10.58		Ahmad <i>et al.</i> , 2012
Peanut Shells	n/a	400°C	n/a	73.2%	n/a	10.5		Gaskin, <i>et al.</i> , 2008
Peanut Shells	n/a	500°C	n/a	80.4%	n/a	10.1		Gaskin, <i>et al.</i> , 2008
Peanut Shells	Air dried, n/a	400°C	40%	59%	0.52	7.9	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak <i>et al.</i> , 2009b

Table 1: Properties of biochars produced via pyrolysis, and associated feedstocks and pyrolysis conditions (*continued*)

FEEDSTOCK	% MOISTURE	PYROLYSIS TEMP	BIOCHAR YIELD WT%	STABLE CARBON YIELD	SURFACE AREA M2/G	PH	OTHER	CITATION
Peanut Shells	Air dried, n/a	500°C	35%	56%	1.22	8.6	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Pecan Shells	Air dried, n/a	350 °C	50%	62%	1.01	5.9	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Pecan Shells	Air dried, n/a	700 °C	30%	53%	222	7.2	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Pine Chips	43%	350 °C	42% est.	71% est.				Masek et al., 2013
Pine Chips	43%	450 °C	31% est.	77% est.				Masek et al., 2013
Pine Chips	43%	550 °C	30% est.	84% est.				Masek et al., 2013
Pine Chips	n/a	400°C	n/a	73.9%	n/a	7.55		Gaskin, et al., 2008
Pine Chips	n/a	500°C	n/a	81.7%	n/a	8.30		Gaskin, et al., 2008
Poultry Litter	10.2%	620°C	44% est.	30.8%	n/a			Ro et al., 2010
Poultry Litter	Air dried, n/a	350 °C	57%	72%	1.10	8.7	Pyrolysis with nitrogen, done with pelletized litter	Novak et al., 2009b
Poultry Litter	Air dried, n/a	700 °C	36%	44%	9.00	10.3	Pyrolysis with nitrogen, done with pelletized litter	Novak et al., 2009b
Poultry Litter	n/a	400°C	n/a	39.2%	n/a	10.1		Gaskin, et al., 2008
Poultry Litter	n/a	500°C	n/a	39.2%	n/a	9.74		Gaskin, et al., 2008
Poultry Litter	Dried 0.31%-6.49%	350 °C	54.3%	27.0%	3.93	8.7	Nitrogen purge 1L/min	Cantrell et al., 2012

Table 1: Properties of biochars produced via pyrolysis, and associated feedstocks and pyrolysis conditions (continued)

FEEDSTOCK	% MOISTURE	PYROLYSIS TEMP	BIOCHAR YIELD WT%	STABLE CARBON YIELD	SURFACE AREA M2/G	PH	OTHER	CITATION
Poultry Litter	Dried 0.31%-6.49%	700 °C	36.7%	35.5%	50.9	10.3	Nitrogen purge 1L/min	Cantrell et al., 2012
Rice Straw	n/a	250 °C	53.7%	63.5%				Peng et al., 2011
Rice Straw	n/a	300 °C	46.2%	67.6%				Peng et al., 2011
Rice Straw	n/a	350 °C	38.9%	66.2%				Peng et al., 2011
Rice Straw	n/a	400 °C	34.6%	69.7%				Peng et al., 2011
Rice Straw	n/a	450 °C	31.9%	72.9%				Peng et al., 2011
Saw Dust	9.9%	500°C	22.6%	80.6%	243.1	9.5		Liu et al., 2014
Softwood Pellets	6%	350 °C	38% est.	72% est.				Masek et al., 2013
Softwood Pellets	6%	450 °C	31% est.	78% est.				Masek et al., 2013
Softwood Pellets	6%	550 °C	28% est.	84% est.				Masek et al., 2013
Soybean Stover	Dried, % n/a	300 °C	37.03%	68.81%	5.61	7.27		Ahmad et al., 2012
Soybean Stover	Dried, % n/a	700 °C	21.59%	81.98%	420.3	11.32		Ahmad et al., 2012
Swine Solids	Dried 0.31%-6.49%	350 °C	62.3%	17.7%	0.92	8.4	Nitrogen purge 1L/min	Cantrell et al., 2012
Swine Solids	Dried 0.31%-6.49%	700 °C	36.4%	33.8%	4.11	9.5	Nitrogen purge 1L/min	Cantrell et al., 2012
Swine Solids	Dried, 12.8%	620°C	35% est.	41.2%	n/a			Ro et al., 2010
Swine Solids blended (29% rye and 71% swine solids, w/w)	Dried, 10.9%	620°C	30% est.	51.6%	n/a			Ro et al., 2010
Solid Fraction of anaerobically digested pig manure (SADPM)	Dried at 60°C for 48 hours, 8.5%	600°C	43.2%	26.2%	17.0	9.3	Nitrogen flow rate 50 cm ³ min ⁻¹	Troy et al., 2013
SADPM mixed 4:1 (w/w) with sawdust	Dried at 60°C for 48 hours, 7.0%	600°C	32.1%	42.3%	19.4	9.0	Nitrogen flow rate 50 cm ³ min ⁻¹ Addition of sawdust significantly decreased biochar yield.	Troy et al., 2013

Table 1: Properties of biochars produced via pyrolysis, and associated feedstocks and pyrolysis conditions (continued)

FEEDSTOCK	% MOISTURE	PYROLYSIS TEMP	BIOCHAR YIELD WT%	STABLE CARBON YIELD	SURFACE AREA M2/G	PH	OTHER	CITATION
SADPM mixed 3:2 (w/w) with sawdust	Dried at 60°C for 48 hours, 7.4%	600°C	30.6%	56.1%	24.4	8.9	Nitrogen flow rate 50 cm ³ min ⁻¹ Addition of sawdust significantly decreased biochar yield.	Troy et al., 2013
Composed SADPM	Dried at 60°C for 48 hours, 9.0%	600°C	49.3%	23.3%	14.2	9.4	Composing reduced 50% mass content, 15% water. Nitrogen flow rate 50 cm ³ min ⁻¹	Troy et al., 2013
Composed SADPM mixed 4:1 (w/w) with sawdust	Dried at 60°C for 48 hours, 6.2%	600°C	39.1%	37.2%	17.4	9.5	Addition of sawdust significantly decreased biochar yield. Nitrogen flow rate 50 cm ³ min ⁻¹	Troy et al., 2013
Composed SADPM mixed 3:2 (w/w) with sawdust	Dried at 60°C for 48 hours, 5.8%	600°C	34.5%	54.7%	23.2	8.7	Nitrogen flow rate 50 cm ³ min ⁻¹ Addition of sawdust significantly decreased biochar yield.	Troy et al., 2013
Switchgrass	Dried and ground, <10%	500°C	41.0%	39.5	50.2		Nitrogen purge 1L/min 125g for 2 h	Brewer et al., 2009
Switchgrass	Dried and ground, <10%	500°C	n/a	26.4%	21.6		Performed on a 5kg/h capacity bubbling fluidized bed reactor	Brewer et al., 2009
Switchgrass	Dried and ground, <10%	760 °C	n/a	34.3	31.4		3 kg/h capacity bubbling fluidized bed reactor using an air/nitrogen fluidizing gas	Brewer et al., 2009

Table 1: Properties of biochars produced via pyrolysis, and associated feedstocks and pyrolysis conditions (continued)

FEEDSTOCK	% MOISTURE	PYROLYSIS TEMP	BIOCHAR YIELD WT%	STABLE CARBON YIELD	SURFACE AREA M2/G	PH	OTHER	CITATION
Switchgrass	Air dried, n/a	250 °C	78%	89%	0.40	5.4	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Switchgrass	Air dried, n/a	500 °C	29%	51%	62.2	8.0	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Turkey Litter	Dried 0.31%-6.49%	350 °C	58.1%	23.1%	2.60	8.0	Nitrogen purge 1L/min	Cantrell et al., 2012
Turkey Litter	Dried 0.31%-6.49%	700 °C	39.9%	29.2%	66.7	9.9	Nitrogen purge 1L/min	Cantrell et al., 2012
Urban Wastewater Sludge	7.6%	300°C	72.3%	Carbon: 25.6% FC: 9.1%		5.32		Hossain et al., 2011
Urban Wastewater Sludge	7.6%	400°C	63.7%	Carbon: 20.2% FC: 6.8%		4.87		Hossain et al., 2011
Urban Wastewater Sludge	7.6%	500°C	57.9%	Carbon: 20.3% FC: 7.6%		7.27		Hossain et al., 2011
Urban Wastewater Sludge	7.6%	700°C	52.4%	Carbon: 20.4% FC: 8.3%		12.00		Hossain et al., 2011





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